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Powder flux regulation in the Laser Material Deposition Process

Jon Iñaki Arrizubieta[a,]*, Maximiliam Wegener[b], Kristian Arntz[b], Aitzol Lamikiz[c], Jose Exequiel Ruiz[c].

[a]*La Caixa's Scholarship Holder. University of the Basque Country (UPV/EHU), Spain*
[b]*Fraunhofer Institute for Production Technology IPT, Germany*
[c]*University of the Basque Country (UPV/EHU), Spain*

Abstract

In the present research work a powder flux regulation system has been designed, developed and validated with the aim of improving the Laser Material Deposition (LMD) process. In this process, the amount of deposited material per substrate surface unit area depends on the real feed rate of the nozzle. Therefore, a regulation system based on a solenoid valve has been installed at the nozzle entrance in order to control the powder flux. The powder flux control has been performed based on the machine real feed rate, which is compared with the programmed feed rate. An instantaneous velocity error is calculated and the powder flow is controlled as a function of this variation using Pulse Width Modulation (PWM) signals. Thereby, in zones where the Laser Material Deposition machine reduces the feed rate due to a trajectory change, powder accumulation can be avoided and the generated clads would present a homogeneous shape.

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Keywords: Laser; powder flux; regulation; solenoid valves

1. Introduction

The Laser Material Deposition (LMD) is a process that is gaining relevance thanks to the advantages that the process offers: High flexibility and the possibility to repair damaged parts with a minimum heat affected zone.

However, there are many points in the LMD process that need to be solved when relatively complex geometries are to be generated. One of the most critical points in the LMD process is obtaining a constant layer height. Due to

* Corresponding author. Tel.: +34 94 601 39 32 .
E-mail address: joninaki.arrizubieta@ehu.eus

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the variations of the substrate geometry, the heat dissipation through the base material is variable, what results in changes in the melt pool size and consequently in the generated clad geometry. Furthermore, due to geometrical restrictions, when the machine reduces the feed rate in order to change the deposition direction or sharp edges are to be generated, a non-uniform machine feed rate is obtained. A non-uniform feed rate leads to variations in the amount of deposited material and in the energy introduced to the substrate per surface unit area; and generates instabilities in the process when overlapping the subsequent layers.

In LMD, process monitoring and control is essential to reduce the amount of rejects and improve the process reproducibility (*Pavlov et al., 2010*). Therefore, during the last decade several authors have focused their efforts on monitoring the laser processes. With the aim of presenting an overview of the non-contact methods used for in-process monitoring of laser processes, *Purtonen et al.* did a review of the latest works in this field (*Purtonen et al., 2014*).

Most authors focus their efforts when monitoring and controlling the LMD processes on the laser power and the amount of heat introduced to the base material. The LMD process control is done in two different ways: a pyrometer can be used for measuring the melt pool temperature and adjust the laser power according to a reference value (*Bi et al., 2006a, Bi et al., 2006b*). Other authors have developed different feedback controls that based on the generated melt pool size, are able to adjust in real time the laser power and keep the melt pool size constant during the deposition process (*Hofman et al., 2012, Ocylok et al., 2014, Ding et al., 2016*). Moreover, authors like *Bi et al.* have gone one step beyond and they have developed a specific laser cladding head that, in addition to different sensors to check the components of the nozzle in real time, includes a CCD camera for monitoring the melt pool size and shape and also an IR signal sensor for temperature measurement (*Bi et al., 2007*).

Nevertheless, when complex geometries are to be obtained, the kinematics of the machine has a big influence in the process, especially when abrupt direction changes are required due to the final shape of the part. At those points, even the melt pool size and temperature can be adjusted by means of a close loop that regulates the laser power, the amount of material that is added to the substrate is increased substantially and therefore the height of the clad is also increased.

This phenomenon was discussed by *Nenadl et al.* and they concluded that the ratio between the powder feeding rate and the scanning speed is directly related to the height of the clad (*Nenadl et al., 2014*). But it was done nothing to correct it. *Boisselier et al.* presented in the LANE-2014 International Conference a trajectory smoothing method that ensured a stable processing (*Boisselier et al., 2014*). But when sharp edges are to be manufactured there is no option for smoothing trajectories.

During the LMD process, the powder flow is controlled by the powder feeder. Usually a powder feeder based on a rotatory disk is used, where the powder flow is regulated by means of the rotation speed of the disk. Some authors have developed a sensing and control system of the powder flow by using an optoelectronic sensor (*Ding et al., 2016*). As it is stated in that article, the key element for achieving a powder delivery control is to measure the powder flow rate in real time. However, although the powder feeder can regulate the amount of powder, usually the response of a conventional powder feeder is not fast enough and no instantaneous powder flux regulation can be carried out using this kind of setup. Furthermore, to gain quick response, the powder flow regulation has to be done once the powder leaves the powder feeder and almost reaches the cladding nozzle. This obliges to use a step-forward control system that is able to predict and anticipate powder variations and actuate before powder accumulation happens.

With the aim of controlling the deposited layer height and eliminate the effect of the powder accumulation due to the machine feed rate reduction, a solenoid based control system has been designed, developed and validated.

2. Experimental setup

The first step when designing the powder flux control system was the analysis of the different alternatives and possible solutions. Two different solutions have been discussed:

1) *Online control*. The machine real feed rate is taken out of the machine drive modules instantaneously and compared with the set-point value send by the machine CNC in order to regulate the powder flux.
2) *Offline control*. The LMD program is run once without switching on the laser nor the powder feeder and a vector of the machine real feed rate regarding to the runtime is obtained from the machine CNC

oscilloscope. Later on, using an external program the real feed rate and the programmed machine feed rate vectors are compared in order to obtain a control program. Lastly, the LMD program is run simultaneously with the control program.

When both solutions are compared, the biggest advantage of the first alternative is the capability to use the control system without any external preprocessor. However, this advantage turns to be a disadvantage itself. As the solenoid responsible for controlling the powder flux is situated upstream the nozzle, when the solenoid commutates its position, the response of the powder flux variation at the addition zone has a delay (the amount of time the powder needs to cover the distance between the solenoid and the melt pool) and therefore the control needs to be forward. This is why an offline control system has been used.

Once the machine real feed rate vector [$\mathbf{v}_r$] is obtained from the machine numeric control, it is compared with the programmed velocity value [$\mathbf{v}_t$] and the "velocity error" [**e**] is defined. On the basis of this "velocity error" vector, a PWM signal is generated, which is used as an input value for the solenoid. Lastly, based on the relative position between the solenoid and the nozzle, and the gas flows, the time forward value is determined in order to compensate the delay of the control.

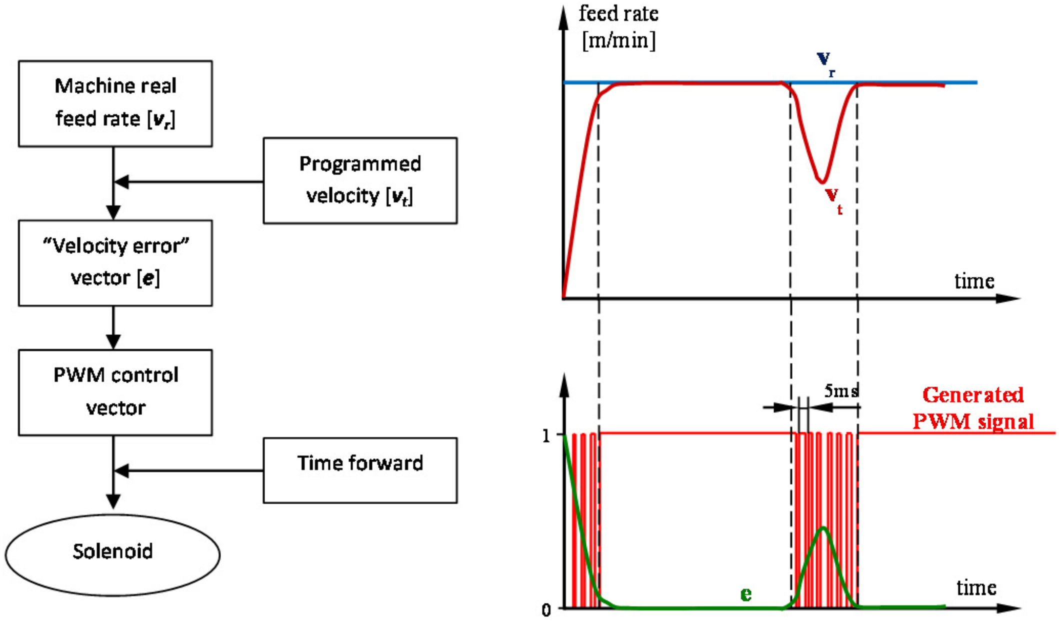

Fig. 1. Scheme of the designed control system and an example of the velocity vectors and the generated PWM signal.

With the aim of obtaining a precise powder flux control, a fast response solenoid from Festo has been chosen. The MHE2-MS1H-5/2-M7-K has a direct electric control with a commutation frequency up to 300Hz (commutation period smaller than 5ms) and cable connection, what enables positioning the solenoid inside the machine, close to the nozzle, whereas the Arduino that controls the solenoid is situated safe outside the LMD machine.

The designed powder control system has been tested in a discrete nozzle, *DCN-EHU V4*, outside the LMD machine and once the systems proper operation has been assured, it is going to be installed in the coaxial nozzle *EHU-Coax2015*, designed and manufactured by the High Performance Manufacturing Group of the University of the Basque Country (*Arrizubieta et al., 2014*). As both nozzles need two gas flows, the schemes shown in Fig. 2 are valid for both cases. The first gas flow is called "protection gas" and it is necessary in order to ensure the durability of the nozzle lenses and also protect the added material from corrosion. The second gas flow is called "drag gas" and is an argon + metallic powder particles mixture. With the aim of controlling the powder flow, the solenoid has been installed in the drag gas pipe as close as possible to the LMD nozzle.

As it is justified in the third point of the present article entitled "3. Simulation", when the drag gas pipe is closed, the existing powder between the outlet 2 of the solenoid and the nozzle needs a gas stream in order to keep constant the velocity of the discrete phase (the powder particles). Therefore a third gas flow, called "extra gas", is connected to the inlet 3 of the solenoid and keeps the gas velocity constant between the outlet 2 of the solenoid and the LMD nozzle.

From now on, position 1 of the solenoid is that in which the drag gas (argon+powder) is directed to the nozzle, whereas position 2 of the solenoid is that in which the extra gas (argon) is directed to the nozzle and the drag gas (argon+powder) is directed to the recycling container.

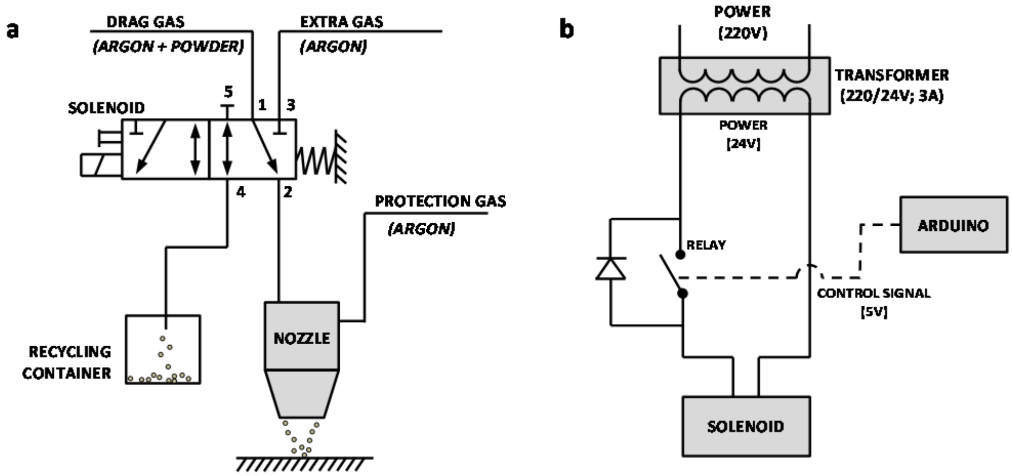

Fig. 2. (a) Scheme of gas and powder pipes and the connection between the nozzle and the solenoid. The scheme represents the rest position of the solenoid, which corresponds to the position 1. (b) Electric scheme of the solenoid control circuit.

The generated error vector (**e**) is converted into a PWM function, see Fig. 1. When the PWM vector has a unit value, the solenoid is in the position 1 (rest position) and that means that powder will get out of the nozzle, whereas a 0 value of the PWM vector means that the solenoid is in position 2 and no powder will get out of the nozzle. This PWM vector, comprised of ones and zeros, is then introduced to an Arduino, which is responsible for the solenoid control. The Arduino generates a 5V voltage PWM output signal and because the solenoid needs 24V, a transformer-relay system has been installed in order to obtain the desired voltage and intensity, see Fig. 2b.

3. Simulation

Based on the experience acquired in previous works related with nozzle design, a key factor in the LMD process is the powder distribution inside the melt pool. Consequently, when the solenoid reduces the powder flow, it is important that the powder distribution remains constant, varying only the maximum and maintaining a Gaussian distribution in the working plane. It is also important that the maximum concentration is maintained at the same distance from the nozzle tip. Therefore, before making the entire assembly described in the section "2. Experimental setup", different simulations of the nozzle have been carried out in order to check the proper operation of developed powder flux regulation system.

The solenoid is able to commutate with a very high frequency, and this results in a lower but constant powder flux downstream. Three different cases have been simulated in order to simulate the different possible working conditions:

1) A 2g/min powder flow is used and no control is applied.
2) A 2g/min powder flow is used, but the solenoid reduces the amount of powder to the 50%, what results in a 1g/min powder flow at the nozzle. In this case, the extra gas is introduced to the nozzle when the "drag gas" flow is interrupted and therefore, the argon gas flow at the nozzle inlets is kept constant with a value of 3l/min.

3) A 2g/min powder flow is used, but the solenoid reduces the amount of powder to the 50%, what results in a 1g/min powder flow at the nozzle. In this case, no "extra gas" is used and therefore, the gas flow that drags the powder is reduced also to the 50%, resulting in a 1.5l/min flow.

The commercial CFD software Fluent from Ansys has been used for the simulations. When determining the boundary conditions in the simulations, the real operation conditions that will be used in the future experimental tests have been fixed, which are detailed in table 1. The duty cycle (DC) of the powder flux control system is the percentage of time where the solenoid is in position 1. As the solenoid changes its state with a high frequency, 20ms, downstream the powder flux can be assumed to be homogenous and reduced proportionally to the duty cycle. This statement is validated later in the section "4. Results". As it is reported, a high speed camera has been used in order to ensure a constant powder stream when the solenoid reduces the powder flow with a 20ms commutation period.

Table 1. Conditions for the simulations.

Simulation case number	1	2	3
Protection gas flow [l/min]	10	10	10
Drag gas flow [l/min]	3	3	1.5
Powder regulation Duty Cycle [%]	100	50	50
Powder mass flow [g/min]	2	1	1

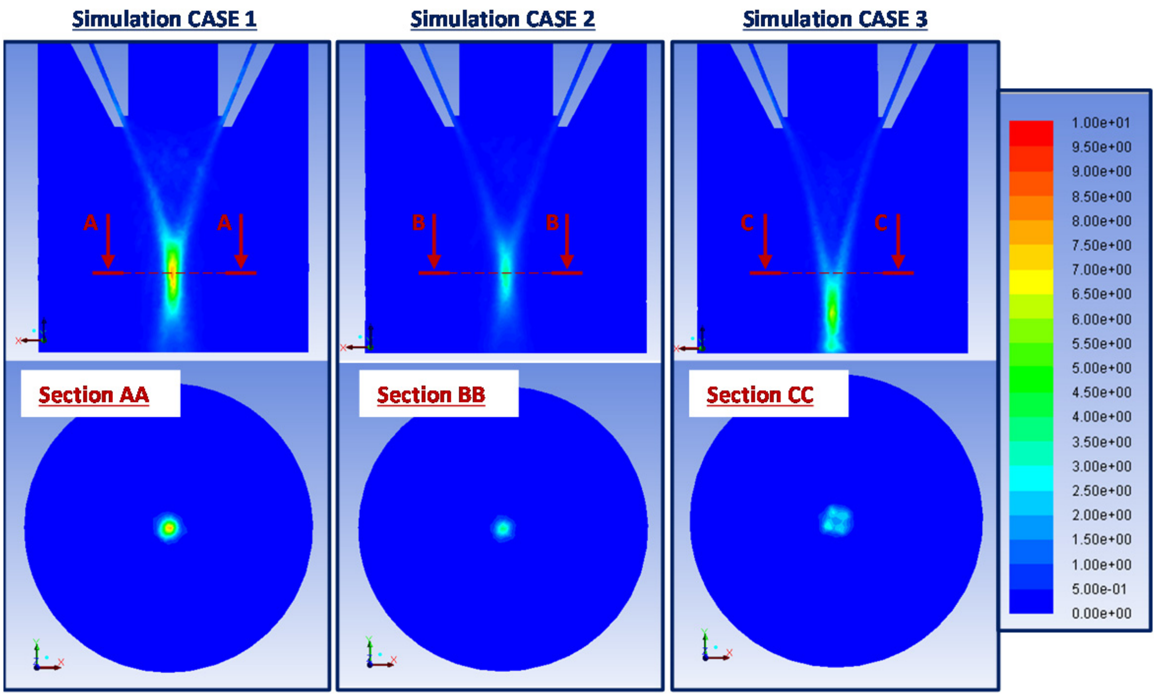

Fig. 3. Powder concentration in [kg/m^3] for the three simulated cases in the ZX plane that comprises the rotation axis of the nozzle and the corresponding XY cross sections at a 16mm distance from the nozzle tip.

As it can be seen, when no extra gas is used, the powder distribution at the nozzle exit changes, what results in an inadequate powder flux regulation system. However, when the "extra gas" is used, the gas flow is maintained constant and the powder flux is reduced proportionally to the PWM signal that controls the solenoid.

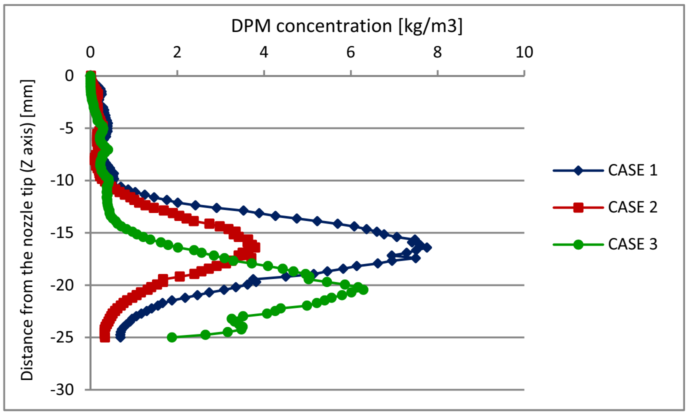

Fig. 4. Comparison of the powder concentration (Discrete Phase Concentration=DPM) in the rotation axis of the nozzle for the three simulated cases. The Z=0 is located at the nozzle tip.

4. Results

Once the viability of the designed powder flux regulation system has been proved by means of the corresponding CFD simulation, the experimental setup described in the second section of the present article has been carried out. With the aim of validating the designed regulation system, first of all it has been tested outside the LMD machine, using the *DCN-EHU V4* four injection discrete nozzle.

The chosen solenoid has a fast response and a high commutation frequency, but it is not designed to work with gas fluxes that drag metallic particles. In order to check the correct functioning of the solenoid, it has been tested with a simple program. A program that changes the position of the solenoid every two seconds has been executed and as it can be seen in Fig. 5, the powder flux changes instantly when the solenoid changes its position from 1 to 2 and from 2 to 1.

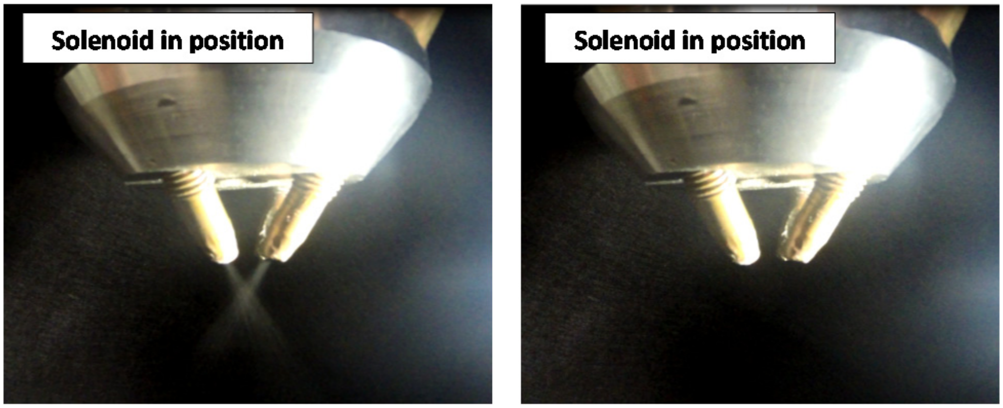

Fig. 5. Two images of the nozzle in different working conditions are shown. The left image corresponds to the “position 1” of the solenoid whereas the right image corresponds to the “position 2” of the solenoid.

Once the correct functioning of the solenoid has been checked, the pipe that connects the exit 4 of the solenoid to the recycling container has been installed (see Fig. 6). In Fig. 6 this pipe is the blue one, but instead of connecting a container at its end, it was left free. Therefore, it can be seen how, when the solenoid switches from position 1 to 2 and no powder comes from the nozzle tip, the powder goes throw this pipe and could be collected in order to reuse it in the future.

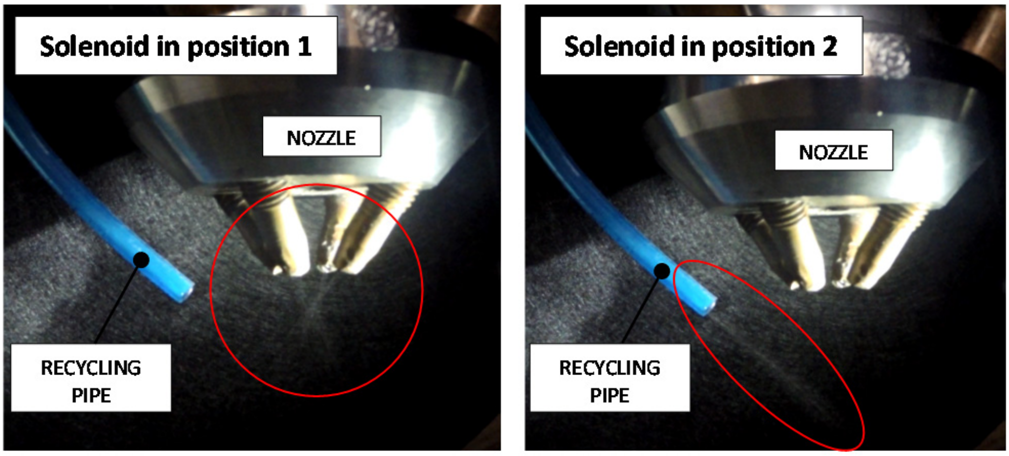

Fig. 6. Two images of the nozzle and the pipe that directs the powder to the recycling container in different working conditions are shown. The left image correspond to the "position 1" of the solenoid whereas the right image correspond to the "position 2" of the solenoid.

As a last test in order to check the correct functioning of the powder flux regulation system, the solenoid has been connected with a 20ms commutation period signal. The solenoid commutation frequency is high enough to generate a homogeneous powder flux downstream, but with a halved mass flow.

A high speed camera has been used to analyse the powder flux outside the nozzle with a 1000fps recording velocity. The resulting powder flux was constant, both at the nozzle exit and the recycling pipe exit.

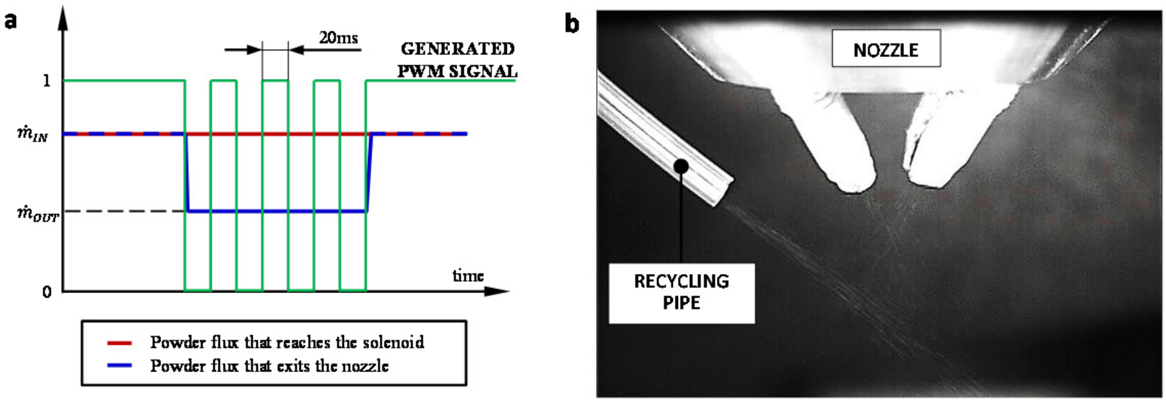

Fig. 7. (a) The PWM signal used and the powder reduction base on it: "$\dot{m}_{IN}$" is the powder flow that reaches the solenoid and "$\dot{m}_{OUT}$" the powder flow that exits the nozzle after the regulation. (b) A screenshot of the high speed camera recording is shown.

Once the proper functioning of the regulation system has been checked, two straight lines were deposited varying the duty cycle of the solenoid. The first line has been deposited with a 100% DC, whereas the second one has been deposited with a 50% DC and a 2 second commutation period; see working parameters in table 2. Consequently, the first line has a constant height, whereas the second one has a dashed line shape. Metallic powder Metcoclad-718 from Oerlikon, with a grainsize between 45 and 125 microns, has been used and in order to guarantee material compatibility an Inconel 718 rod with a 40x40mm cross section has been used as a substrate.

Table 2. Conditions for the experimental tests.

Line number	Powder [W]	Machine feed rate [mm/min]	Powder mass flow [g/min]	DC [%]	Commutation frequency [Hz]
1	500	500	2	100	1
2	500	500	2	50	0.5

In order to check the variations in height of the second line, the topography of the clad has been obtained using a Leica DCM 3D confocal microscope. As it can be seen in Fig. 8, clad height variation when the solenoid changes from position 1 to 2 and vice versa is extremely rapid. Thus, it can be concluded that the powder flux regulation system is instantaneous.

When lines 1 and 2 are to be compared, in the second line the clad height is constant throughout the time when he solenoid is in position 1 and matches the first clad height, what means that there is no powder accumulation inside the regulation system when the solenoid is in position 2. In both clads an average height of 125µm is obtained.

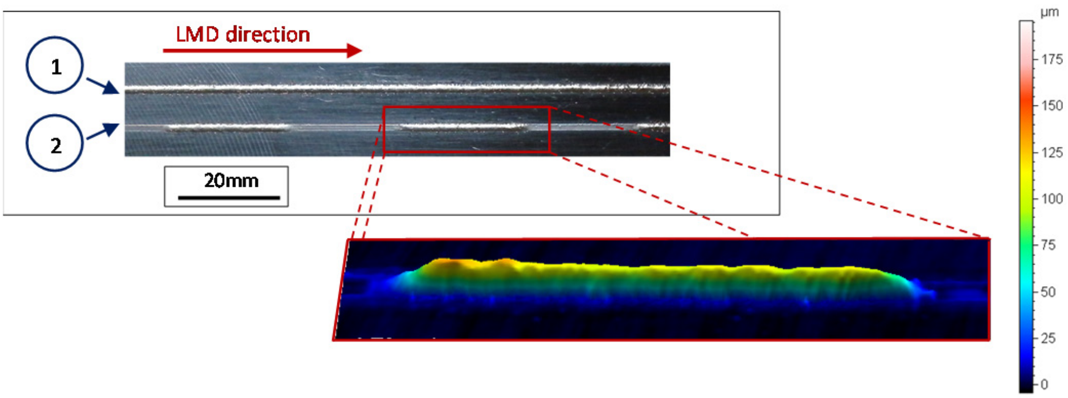

Fig. 8. Clads 1 and 2 deposited in order to validate the designed powder flux regulation system and a topography of the second clad when the solenoid is in position 1.

5. Conclusions

A new regulation system based on the powder flux regulation for the LMD process has been designed, developed and validated.

The obtained results are very promising. On the one hand, the powder flux can be stopped when the laser is off and therefore the amount of wasted powder is reduced, what is really relevant for long void movements. Besides involving economic advantages, the possibility to cut the powder particle flux when the laser is off, means a cleaner process. On the other hand, the powder that is stored in the recycling container can be reused with no drawbacks to the process, because it has not been remelted by the laser or contaminated inside the machine by previously used powders or atmospheric dust.

However, the most important benefit of the designed powder flux regulation system is the possibility to control the deposited clad height. The clad height is proportional to the amount of material introduced per unit area of the substrate. Therefore, controlling the powder flux, the clad height can be controlled and kept constant. This regulation system is very important for complex geometries and specially for 5 axis LMD process and in the future more work will be done in this direction.

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